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CP VIOLATION: PRESENT AND FUTURE

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ABSTRACT

Our theoretical understanding of CP-violating phenomena is reviewed. I show that CPT is still a good symmetry and proceed to investigate the origin of CP-violation. I review the theoretical models and apply them to the interpretation of ε_K , $(\varepsilon'/\varepsilon)_K$ and B-meson decays. Finally the role of CP-violation in the creation of the baryon asymmetry of the universe is reviewed.

Introduction

The origin of CP-violation together with the origin of the Higgs mechanism are the two unsolved problems of the electroweak theory. They constitute two remaining frontiers of the standard model. CP-violation is important because it concerns a fundamental symmetry of nature. It is also part of a larger symmetry CPT, whose validity has been tested to a good degree of accuracy.

In this talk I did not attempt to make an exhaustive review; there are plenty of those. Instead I will review topics where there was progress during the past two years and I will ask the question. "What are the important topics and issues which remain open and must be investigated in the future?"

The outline of my talk is the following:

1. Status of CPT-invariance
2. Origin of CP-violation (especially in gauge theories)
3. Observables in the K^0 -meson system
4. The promised land of B-mesons
5. Connection of CP asymmetries to Baryogenesis
6. Present and Future

This is a slightly extended version of the Invited Talk presented at the 27th Lepton-Photon Symposium, Beijing, China (August 1995) and at the 5th Hellenic School and Workshop on Elementary Particle Physics, Corfu, Greece (September 1995).



So far CP asymmetries have been observed in the laboratory in experiments with K^0 mesons: K -long and K -short. They are also observed, indirectly, in the large scale structures of the universe through the Baryon asymmetry.

1. Status of CPT Invariance

1.1 CPT Violating Theories

The CPT symmetry follows from the general assumptions and structure of quantum field theories (QFT). It is interesting to ask, "Can we formulate CPT violating theories?" One way is to construct theories, where the Whightman functions in the forward light-cone are not related to the Whightman functions in the backward light-cone.¹ In this case the masses for particles and antiparticles are different.

We know very few examples of theories where CPT is broken. There is an old theory by Osak and Todorov¹, which involves infinite component theories and there is a model by Bigi² which breaks CPT and Lorentz invariance at the same time. Now that we know to break discrete and continuous symmetries spontaneously, we may try, as a second possibility, to break CPT also spontaneously. This entails the construction of QFT with vacua that transform differently under CPT and mix with each other. I do not know of any consistent theory where CPT is spontaneously broken. Finally, we have experimental evidence that C, P, and CP are separately broken, but all experimental evidence, so far, is consistent with CPT invariance.

1.2 Consequences of CPT invariance

The tests of CPT conservation are very restrictive. I tabulate below three consequences of CPT symmetry together with the experimental bounds.

(i) The masses for particles and antiparticles must be equal:

	<u>Bound</u>	<u>Experiment</u>
$\frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}}$	$< 3.5 \cdot 10^{-18}$	NA 31 ³
	$< 1.3 \cdot 10^{-18}$	E 773 ⁴
	$< 1.8 \cdot 10^{-18}$	CP-LEAR ⁵

(ii) The phases of the η_{00} and η_{+-} parameters must be equal. Denoting the phases by ϕ_{00} and ϕ_{+-} , respectively, the difference

$$\Delta\phi = \phi_{00} - \phi_{+-} = 0. \quad (1)$$

Experimentally it has been established that

$$\begin{aligned} \Delta\phi &= 0.2^\circ \pm 2.6^\circ \pm 1.2^\circ & \text{NA 31}^3 \\ &= 0.62^\circ \pm 0.71^\circ \pm 0.75^\circ & \text{E 773}^4. \end{aligned}$$

iii) Excluding unexpected large CP-violation in decays other than $\pi\pi$, it also follows

$$\phi_{+-} \approx \phi_{sw} = \tan^{-1} \left(\frac{-2\Delta m}{\Gamma} \right). \quad (2)$$

The value of ϕ_{sw} is

$$\phi_{sw} = 43.37^\circ \pm 0.17^\circ.$$

The experiments measured the values

	<u>Value</u>	<u>Experiment</u>
ϕ_{+-}	$= 46.0^\circ \pm 2.2^\circ \pm 1.1^\circ$	NA 31 ³
	$= 43.53^\circ \pm 0.58^\circ \pm 0.47^\circ$	E 773 ⁴
	$= 43.2^\circ \pm 0.9^\circ \pm 0.6^\circ \pm 0.7^\circ_{\Delta m}$	CP-LEAR ⁵

All the values are consistent with each other and very close to the superweak phase.

1.3 The phase of the strong amplitude in the regeneration of K_s

The two experiments NA31 and E773 are very different. NA31 measures ϕ_{+-} and ϕ_{00} separately. The E773 experiment uses a regenerator to produce the K_s beam and measures the difference $\phi_{+-} - \phi_r$ where ϕ_r is the phase of the strong amplitude that produces the K_s (regeneration phase). The phase ϕ_r is determined by using both theory and experimental data.

A controversy arose over the past two years concerning the determination of ϕ_r . Kleinknecht and Luitz⁶ argue that the phase ϕ_r has theoretical uncertainties much larger than 0.5° . Briere and Winstein respond in a recent article⁷, "... including many possible corrupting effects, the uncertainty is well below 1° ." In such a situation the angle ϕ_r should be computed by other groups and reported as a function of the beam energy. Finally the new experiment KTeV will measure ϕ_r directly with a precision better than one degree.⁸

The CP-LEAR experiment is again different and is based on the production of tagged K^0 or \bar{K}^0 at low energies. The experiment observes the time development of the particles and establishes a difference in their decay rates for the time interval between 6 and 18 K-short lifetimes. It provides independent evidence, discussed in detail by P. Franzini in the previous talk. The time asymmetries which are observed in CP-LEAR are representative of the time asymmetries to be searched for in B^0 and \bar{B}^0 decays.

To conclude, there are very accurate measurements for CPT conservation and for the rest of the talk I will assume CPT invariance. We also expect additional tests of CPT symmetry from the KLOE detector in DAΦNE, which will also measure the overlap of the $K^0(t)$ and $\bar{K}^0(t)$ wave functions⁹.

1.4 Time Reversal

The time reversal transformation changes the direction of time, i.e. $t \rightarrow -t$. Classically, the transformation reverses the velocities of a reaction and the system traces its way back to the original configuration. In quantum mechanics time reversal changes also the phases of amplitudes and predicts

- i) Reciprocity relations, and
- ii) Phase-angle relations of amplitudes¹⁰.

Reciprocity relations have been tested in strong interactions to an accuracy of 0.5%. The reciprocity relation can also be tested in reactions mediated by the weak interactions. For instance one can measure the asymmetry

$$A_\ell(t) = \frac{|\bar{K}^0, t|T|K^0, 0\rangle|^2 - \langle K^0, t|T|\bar{K}^0, 0\rangle|^2}{\langle \bar{K}^0, t|T|K^0, 0\rangle|^2 + \langle K^0, t|T|\bar{K}^0, 0\rangle|^2}$$

known as the Kabir test¹¹. This ratio is predicted to be¹²

$$A_\ell(t) = 4Re\varepsilon_T - 2Rey_\ell .$$

The two terms on the right-hand side have different origins. The parameter ε_T describes the failure of T invariance. The second term Rey_ℓ originates from direct CP- and CPT-violation in the decay

$$K^0 \rightarrow \pi^- \ell^+ \nu.$$

This asymmetry $A_\ell(t)$ was measured in the CP-LEAR experiment and was found with good accuracy to be equal to $4Re\varepsilon_K$ ⁵. This result implies two things:

- i) The CPT-violating term Rey_ℓ is small, and
- ii) the value of $Re\varepsilon_T$ is consistent with $Re\varepsilon_K$ measured in the lepton asymmetry of K_{long} decays.¹¹

One may ask, "Is this measurement a test of time reversal?" It seems to me that it is, because it exchanges the initial with the final states. The transformation also exchanges particles with antiparticles and vice versa. Thus the experiment implies that CPT-violation in K_{ℓ_3} decays is small and the numerical value for T-violation is equal to the CP-violation.

2. Origin of CP Violation

The aim of all investigations on this topic is to discover the origin of the effect. At this time we do not know the origin of the CP asymmetries. In such a situation it

is useful to make consistent hypotheses which can be either disproved by experiments or guide us to the origin of the effect. There are several popular proposals.

The superweak theory of Wolfenstein states that all CP-asymmetries occur in $\Delta S = 2$ transitions and by a simple extension in $\Delta B = 2, \dots$ transitions. It allows $\epsilon_K \neq 0$ but predicts $(\epsilon'/\epsilon)_K = 0$. The experimental evidence so far

$$\begin{aligned} (\epsilon'/\epsilon) &= (23.0 \pm 3.6 \pm 5.4) \cdot 10^{-4} \quad \text{NA 31}^{13} \\ &= (7.4 \pm 5.2 \pm 2.9) \cdot 10^{-4} \quad \text{E 731}^{14} \end{aligned}$$

is inconclusive. The ultimate accuracy of the new experiments will be $(1 \text{ to } 2) \cdot 10^{-4}$ and they should decide this point.

The second origin of CP-violation is a phase in the charged-current couplings of the Cabibbo-Kobayashi-Maskawa matrix. This is the CKM Paradigm. It is not a property only of the electroweak theory, but a convenient parametrization of various theories: standard model, Left-Right symmetric theories, phases in the Higgs potential, etc. The CKM Paradigm will be tested extensively with B-mesons, as I discuss in section 4.

In case that (ϵ'/ϵ) turns out to be less than 10^{-4} , it points to the superweak theory. On the other hand, if the new experiments establish by 1998 that $(\epsilon'/\epsilon) \neq 0$ then there are several theories that produce the effect. I describe next two popular origins of the effect.

In gauge theories CP-violation occurs in the Yukawa couplings and the Higgs potential. In gauge theories with chiral fermions the CP and P transformations are automorphic to the algebra of the group.¹⁵ Thus breaking the group, we can select to break a generator which also breaks CP. We now discuss several cases :

(i) In the standard model with a single Higgs doublet the phase of the vacuum expectation value (vev) can be absorbed in the phase of the physical Higgs field. Thus a complex phase is introduced by hand arbitrarily in the Yukawa couplings. We call this explicit violation of CP-symmetry.

(ii) In the minimal extension of the standard model with two Higgs doublets there are two vev's which are complex. One phase is absorbed in the phase of the scalar field, but the second one survives. We call this case spontaneous breaking of the symmetry as was described in the pioneering work of T.D. Lee.¹⁶ This case and its consequences were discussed recently by several groups.^{17,18,19} One consequence is in the charged Higgs sector. In the model there are charged Higgses which survive as physical particles. Their couplings to fermions are now complex¹⁸:

$$\mathcal{L}_H^+ = \sqrt{2} \xi_{dj} m_{dj} V_{ij} \bar{u}_L^i d_R^j H^+ + \dots \quad (3)$$

where V_{ij} is the CKM-matrix, ξ_{dj} a 3x3 matrix with phases in the diagonal elements only and zeros everywhere else, and m_{dj} the mass of the j^{th} down quark. The charged

Higgses bring new contributions to $\varepsilon_K, (\varepsilon'/\varepsilon)_K$ and the electric dipole moments. For instance, $(\varepsilon'/\varepsilon)_K$ can have values between 10^{-5} all the way up to 10^{-3} , and electric dipole moments

$$\begin{aligned} &\text{for the neutron } D_n \sim 10^{-25} \text{ to } 10^{-26} \text{ e} \cdot \text{cm}, \text{ and} \\ &\text{for the electron } D_e \sim 10^{-26} \text{ to } 10^{-27} \text{ e} \cdot \text{cm} \end{aligned}$$

are allowed. The standard model predicts electric dipole moments which are much smaller. This is one group of measurements that can distinguish between the two models.

(iii) There are many extensions of the standard model where CP is not conserved. Several of them appear in contributions to this conference and I mention them briefly:

- (α) There are models with more singlets whose weak interactions were studied in detail.²⁰
- (β) A model with an extra singlet in E(6).²¹ Silverman studied the constraints on the mixings of the singlet to be reached at the B-factories.
- (γ) Supersymmetry modifies many predictions of the standard model including CP-asymmetries.²²
- (δ) There are models with more fermion multiplets, like a fourth generation.²³

In summary, it is possible in gauge theories to break the CP-symmetry explicitly or spontaneously. In contrast to the CPT-symmetry, there are many examples where the CP-symmetry is broken and the various models make different predictions. For the rest of this talk, I will adopt the CKM Paradigm and discuss its predictions.

3. CP Observables in the K^0 -Meson System

3.1 Indirect CP Violation: ε_K

We know from the leptonic asymmetry of the $K_L \rightarrow \pi^- e^+ \nu$ and $K_L \rightarrow \pi^+ e^- \bar{\nu}$ decays, that the states $|K_L\rangle$ and $|K_S\rangle$ are not CP eigenstates. Thus CP is violated in the mass-matrix. This phenomenon is described by the parameter ε_K , which is calculated from the imaginary part of the box diagrams shown in figure 1.

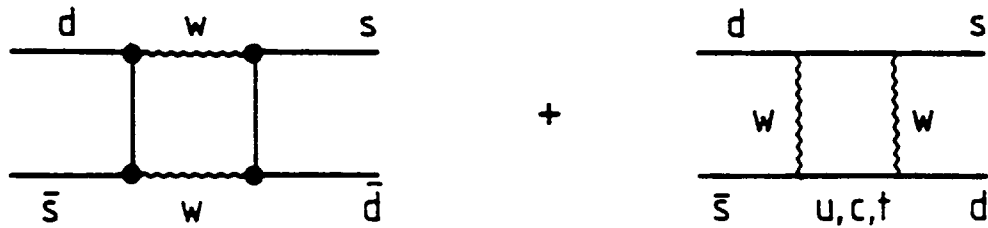


Fig. 1. The box diagrams.

The final expression of this calculation is

$$|\varepsilon_K| = \frac{G_F^2 f_K^2 M_K M_W^2}{6\sqrt{2}\pi^2 \Delta M_K} B_K (A^2 \lambda^6 \eta) [\eta_c E(x_c) - \eta_{ct} E(x_c, x_t) - \eta_t E(x_t) A^2 \lambda^4 (1 - \rho)]. \quad (4)$$

The constant B_K is the Bag-factor occurring in the hadronic matrix element of the four-quark operator. The parameters A , λ , η and ρ are the parameters of the CKM matrix in the Wolfenstein parametrization. $E(x_c)$, $E(x_c, x_t)$ and $E(x_t)$ are the functions from the loop-integration known as the Inami-Lim functions and depend on $x_q = m_q^2/M_W^2$. Finally, η_c , η_{ct} and η_t are the QCD corrections to the functions $E(x_c)$, $E(x_c, x_t)$ and $E(x_t)$, respectively. They are produced by the exchange of gluons in all possible ways.

During the past year there appeared several theoretical improvements on the calculations of ε_K which I discuss. The discovery of the top quark was a great bonus because with the mass of the top quark we have precise values for the functions $E(x_c, x_t)$ and $E(x_t)$. The second improvement is a better understanding of the QCD factors. The factors were originally calculated for a top quark lighter than the W-boson by two different methods,^{24,25} which had a long-standing and unsettled issue raised in ref. 25. To be specific, even for $m_t \ll m_w$ the two calculations did not agree for η_{ct} . It was shown recently²⁶ that the apparent disagreement between the two articles is a consequence of certain simplifying assumptions in ref. 24. By considering the threshold factors correctly it was shown algebraically to be equivalent. The calculations have also been extended in the case $m_t = 174 \pm 25 \text{ GeV}$.²⁶ In addition there are two other improvements: ref. 27 calculated next-to-leading correction for η_t and ref. 26 also includes the renormalization region $m_w \leq p \leq m_t$. The final values are $\eta_t = 0.58^{26,27}$ and $\eta_{ct} = 0.37^{26}$ which are close to the original values.²⁵

The third improvement is on the elements of the CKM-matrix where the values²⁸

$$|V_{cb}| = 0.039 \pm 0.006 \quad \text{and} \quad |V_{ub}/V_{cb}| = 0.08 \pm 0.03$$

are used. Finally, there is the overall factor B_K for which there are new values from lattice QCD.²⁹ Allowing $0.6 < B_K < 1.0$ the parameters η and ρ are restricted to the shaded region of figure 2. We notice that they are restricted to $0.2 < \eta < 0.4$ and $-0.35 < \rho < 0.30$.

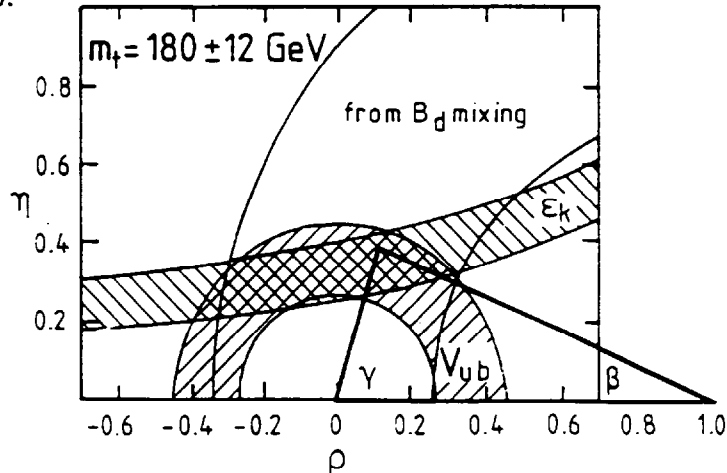


Fig. 2. The CKM triangle overlaid upon constraints in the $\eta - \rho$ plane (ref. 30).

Several groups^{30–32} carried out this analysis and when they use more restrictive values of the input data, the parameters η and ρ are almost unique.^{31,32} To sum up, there is now better understanding for the calculation of ε_K , which restricts η and ρ to limited ranges given above.

3.2 Direct CP-violation: $(\varepsilon'/\varepsilon)$

The second parameter ε' measures the CP-violation in the $\Delta S = 1$ decay amplitudes. It is calculated from the equation

$$\frac{\varepsilon'}{\varepsilon} = \frac{1}{\sqrt{2}} \frac{1}{|\varepsilon_K|} \left(\frac{\text{Im } A_2}{A_0} - \frac{\text{Im } A_0}{A_0} \right) \quad (5)$$

with A_0 and A_2 the decay amplitudes

$$A_0 = A(K^0 \rightarrow 2\pi, I=0) \quad \text{and} \quad A_2 = A(K^0 \rightarrow 2\pi, I=2) .$$

These amplitudes are calculated from the effective Hamiltonian for $\Delta S = 1$ transitions

$$H_{eff}^{\Delta S=1} = \frac{G}{\sqrt{2}} \xi_c \sum_i C_i(p) Q_i \quad (6)$$

derived by renormalization group methods. For the problem considered, we must calculate matrix elements between $|K^0\rangle$ and $|\pi\pi\rangle$ states. I describe briefly the various factors occurring in the Hamiltonian and then I come to the main issue remaining in these calculations. The factor ξ_c depends on CKM matrix elements and for our problem only its imaginary part is relevant

$$\text{Im } \xi_c = -\text{Im } V_{td} V_{ts}^* = A^2 \lambda^5 \eta. \quad (7)$$

The new values for the mixing angles and the limits on η (see section 3.1) determine $\text{Im } \xi_c$ within a factor of ~ 2 .

The coefficient functions $C_i(p)$ are obtained from renormalization from high energies down to the momentum p . They were computed in QCD first to lowest order^{33,34} subsequently in next-to-leading order.^{34,35} The values from the various groups agree with each other. There remain the matrix elements

$$\langle Q_i \rangle_{0,2} = \langle \pi\pi; I=0,2 | Q_i | K^0 \rangle \quad (8)$$

which describe the long-distance contribution. They are computed through factorization or to lowest order in chiral perturbation theory, which are equivalent methods. There are eight of these operators, but taking the values of the coefficient functions and the values of the matrix elements, it was shown that the dominant contribution comes from two operators: Q_6 and Q_8 . Thus the expression for the ratio simplifies to

$$\frac{\varepsilon'}{\varepsilon} = -\frac{G}{\sqrt{2}} \frac{1}{|\varepsilon| |A_0|} (\text{Im } V_{td} V_{ts}^*) C_6 \langle Q_6 \rangle \left\{ 1 - \frac{1}{\omega} \frac{C_8 \langle Q_8 \rangle_2}{C_6 \langle Q_6 \rangle} \right\} \quad (9)$$

with $\omega = \frac{1}{22}$. The operator $\langle Q_6 \rangle$ describes a $\Delta I = \frac{1}{2}$ transition and $\langle Q_8 \rangle_2$ a $\Delta I = \frac{3}{2}$ transition. In fact

$$Q_6 = -2 \sum_q \bar{s} (1 + \gamma_5) q \bar{q} (1 - \gamma_5) d \quad (10)$$

is produced by the gluon penguins and

$$Q_8 = -3 \sum_q Q_q \bar{s} (1 + \gamma_5) q \bar{q} (1 - \gamma_5) d \quad (11)$$

by the electroweak penguins. The relative magnitudes of the terms $C_8 \langle Q_8 \rangle_2$ versus $C_6 \langle Q_6 \rangle$ are very important because they determine if the expression in the curly brackets of Eq. (9) vanishes or not. In addition, $C_6 \langle Q_6 \rangle$ is also important because it determines the overall scale. The important issue is to understand the matrix elements. For this reason I reviewed the various methods developed for calculating the matrix element and will present them in the next section.

Before I leave this section, a word of caution. The effective Hamiltonian in Eq. (6) sums up the leading logarithmic terms of QCD and ignores higher twist operators. We have no reason to believe that they are there, nor can we exclude them with rigorous arguments.

3.3 Hadronic Matrix Elements

To lowest order in chiral perturbation theory the matrix elements are given by the relations³⁶

$$\langle Q_6 \rangle = -4 \sqrt{\frac{3}{2}} \frac{m_K^2}{m_s^2} f_\pi \frac{m_K^2 - m_\pi^2}{\lambda^2} B_6 = -0.35 B_6 \text{ GeV}^3 \quad (12)$$

and

$$\langle Q_8 \rangle_2 = \sqrt{3} \frac{m_K^4}{m_s^2} f_\pi B_8 = 0.45 \cdot B_8 \text{ GeV}^3 \quad (13)$$

for $m_s = 150 \text{ MeV}$, $f_\pi = 93 \text{ MeV}$ and $\lambda = 900 \text{ MeV}$. The factors B_6 and B_8 are equal to one and are introduced in order to denote deviations from the lowest order results. The above values with $B_6 = B_8 = 1$ are benchmark values for comparisons with other calculations. They are obtained from the diagram in fig. (3a). In the diagrams the squares indicate weak vertices and the circles strong interaction vertices.

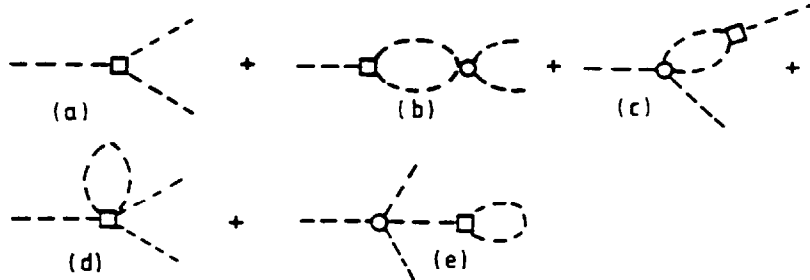


Fig. 3. Chiral diagrams for K decays including rescattering corrections.

To this result we must add the rescattering of the mesons in the final state illustrated by the last four diagrams in fig. (3). The rescattering of mesons gives important corrections for the π - π phase shifts. Since the theory has infinities at one loop they are computed with an energy cut-off. One-loop calculations for the operators Q_1 and Q_2 were reported by Bardeen, Buras and Gerard³⁶ where an enhancement was found for the $\Delta I = \frac{1}{2}$ amplitude. The calculation was extended to the Q_6 and Q_8 operators with the results³⁷

$$\langle Q_6 \rangle_{I=0} = -\sqrt{\frac{3}{2}} \frac{r^2 m_K^2}{f \lambda^2} \left[f^2 + \frac{5m_K^2}{64\pi^2} \ln\left(1 + \frac{M_{cut}^2}{\tilde{m}^2}\right) + \frac{3M_{cut}^2}{32\pi^2} \right], \quad (14)$$

$$\begin{aligned} \langle Q_8 \rangle_{I=2} = & -\frac{r^2}{\sqrt{3}f} \left\{ -\frac{3}{4}f^2 + \frac{71}{384\pi^2} \frac{m_K^2 M_{cut}^2}{\lambda^2} + \frac{9}{128} \frac{M_{cut}^2}{\pi^2} \right. \\ & \left. + \ln\left(1 + \frac{M_{cut}^2}{\tilde{m}^2}\right) \frac{m_K^2}{\pi^2} \left(-\frac{5m_K^2}{1152\lambda^2} - \frac{3}{64} \right) \right\}. \end{aligned} \quad (15)$$

The net effect is an enhancement of $\langle Q_6 \rangle$ and a large decrease for $\langle Q_8 \rangle_2$. Consequently the cancellation in the curly bracket of Eq. (9) does not occur anymore and $(\varepsilon'/\varepsilon)$ remains positive.

There are several new developments on this topic:

1) In an early paper³⁸, we reported that $Im A_0 \propto C_6 \langle Q_6 \rangle$ is increased by 30% and $Im A_2 \propto C_8 \langle Q_8 \rangle_2$ is decreased by 30%. In the same article we pointed out, since there is only one pseudoscalar meson operator $(\partial_\mu U \partial^\mu U^+)^{ab}$ there exist relations among the quark operators. In particular

$$Q_6 = \frac{r^2}{\lambda^2} (Q_1 - Q_2) = -\frac{11}{2} Q_4. \quad (16)$$

2) In a recent paper Fatelo and Gerard³⁹ study the renormalization of the quark operators from high energies to the chiral scale λ , where they match them with the scalar meson operators. Since there is, to $O(p^2)$, only one meson operator they find a consistency relation:

$$Q_6(\lambda) = -\frac{11}{2} Q_4(0) + O\left(\frac{1}{N}\right). \quad (17)$$

This is the same equation as given above. Now, taking the values for Q_1 and Q_2 from ref. 36, which includes the one-loop corrections, we find that $\langle Q_6 \rangle$ increases so that the zero in $(\varepsilon'/\varepsilon)$ is eliminated.

3) A recent calculation using QCD sum rules⁴⁰ finds $\langle Q_6 \rangle = -0.40$.

4) Finally, a lattice gauge theory calculation³⁵ finds

$$B_6 = 1.0 \pm 0.20 \quad \text{and} \quad B_{7,8}^{3/2} = 1.0 \pm 0.20. \quad (18)$$

In the last calculation the matrix elements are computed, for technical reasons, at the scale $p = 2.0 \text{ GeV}$ and it is subsequently assumed that the products $C_i(p)\langle Q_i \rangle$ remain constant when p is reduced to m_K .

To sum up, the chiral calculations for $\langle Q_6 \rangle$ and $\langle Q_8 \rangle_2$ are consistent with each other. Most of them are to lowest order. One of the calculations^{37,38} included one-loop corrections which modify the lowest-order results. Recent articles described in items 2) and 3) above support the magnitude of the corrections found in one-loop. The lattice calculation, item 4), finds smaller corrections. The errors reported for the lattice calculation are uncorrelated and if I take the positive value for $B_6 = 1.20$ and the negative error for $B_8^{3/2} = 0.80$, then also the lattice results eliminate the zero or very small value for $(\varepsilon'/\varepsilon)$.

The predictions of the three groups are the following:

Group	$(\varepsilon'/\varepsilon)$	$1 - \Omega_8$
Rome	$(3.1 \pm 2.5 \pm 0.3) \cdot 10^{-4}$	maybe a zero
Munich	$(6.7 \pm 2.6) \cdot 10^{-4}$	No zero
Dortmund	$(9.9 \pm 4.1) \cdot 10^{-4}$ for $m_s = 175 \text{ MeV}$	No zero

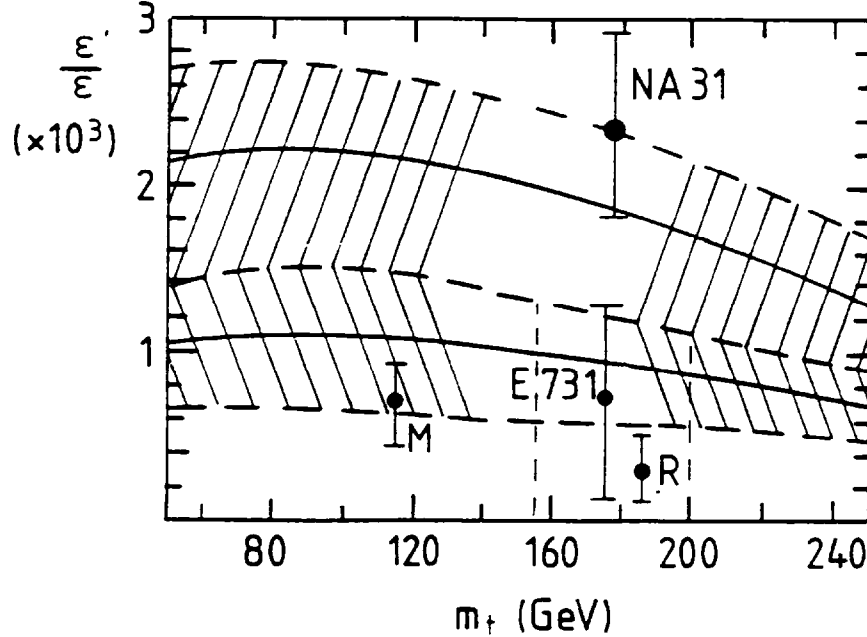


Fig. 4. The ratio ε'/ε as a function of m_t . The upper shaded region is for $m_s = 125 \text{ MeV}$ and the lower for $m_s = 175 \text{ MeV}$.

I also show in fig. (4) the calculations from Munich (M, for $m_s = 150 \text{ MeV}$, Rome

(R) and Dortmund (two shaded regions), together with the experimental data as a function of the top quark mass. The recent developments support a positive and measurable value. Among the results the prediction from the Dortmund group is large enough to be confirmed or disproved in the next round of experiments.

4. The Promised Land of B-mesons

Testing the CP symmetry with B-mesons is very promising, because asymmetries which are small in K-mesons become sizable for B-mesons. This capability will provide, eventually, a complete test of the CKM Paradigm. In addition, the heavy mass of the B-states makes possible reliable estimates of hadronic matrix elements or ratios of them. These properties make B-meson experiments attractive. However, the short lifetimes and the small branching ratios render the observation of CP-asymmetries difficult. Luckily, our experimental colleagues are developing ingenious methods in order to overcome the difficulties.

4.1 Comparisons between K^0 and B^0 Mesons

The properties of the neutral K and B meson systems are quite different. For the K-mesons there are two physical states with very different lifetimes:

$$\tau(K_s) = 89.26 \text{ ps} \quad \text{and} \quad \tau(K_L) = 51700 \text{ ps}. \quad (19)$$

This difference comes about because the mass- and lifetime difference in the K-mesons are comparable:

$$\Delta M_K = \frac{1}{2} \Delta \Gamma_K = -\frac{1}{2} \Gamma_s. \quad (20)$$

For the B-mesons the situation is very different. The lifetime of the B-mesons is much smaller:

$$\tau(B) = (1.55 \pm 0.06) \text{ ps}. \quad (21)$$

In addition $\Gamma_{12} \ll M_{12}$ for B-mesons which makes the lifetimes of the two physical states almost identical. For this reason they are characterized by their masses as heavy and light, and are denoted by B_H and B_L , respectively. From the mixing of the two states we know their mass difference.

$$\frac{\Delta M}{\Gamma} = 0.71 \pm 0.06. \quad (22)$$

The mixing of the B-states is described by diagrams analogous to those in fig. (1) with the top quark dominating in the intermediate states. Computation of the diagrams gives the mixing parameter ε_B , as

$$\frac{q}{p} = \frac{1 - \varepsilon_B}{1 + \varepsilon_B} \approx \frac{V_{td}}{V_{td}^*} = e^{-2i\beta} \quad (23)$$

with β the phase of the V_{td}^* matrix element.

It follows from this discussion that ε_B is mostly imaginary with a very small real part. Consequently, the leptonic asymmetry in the decays of B-mesons, which is proportional to $\text{Re}\varepsilon_B$, is too small to be seen in the early rounds of the experiments. For this reason another method was proposed and developed for observing CP-violation.

4.2 A General Property

A CP-violating phase is frequently generated in decay amplitudes, and in order to be observable it is necessary to interfere this amplitude with another amplitude. For the B^0 -mesons it is possible to produce the states B_H and B_L coherently. For instance,

$$B_{H,L} = \frac{1}{N} \left[|B^0\rangle \pm \frac{q}{p} |\bar{B}^0\rangle \right] \quad (24)$$

with N a normalization factor and q/p defined in Eq. (22). The factor q/p introduces a phase. In addition to this there is also a phase in the transition amplitudes

$$A_f = \langle f|H|B^0\rangle \quad \text{and} \quad \bar{A}_f = \langle f|H|\bar{B}^0\rangle \quad (25)$$

with $\langle f|$ a common final state. The latter phase can be changed by redefining the phase of the state $|B^0\rangle$. For instance, instead of $|B^0\rangle$ we may consider the state $e^{i\alpha}|B^0\rangle$. Physical observables should be invariant under this phase transformation. Quantities invariant under the above rephasing are

$$\frac{q}{p} \frac{\bar{A}_f}{A_f} = e^{-2i\beta} \frac{\bar{A}_f}{A_f}. \quad (26)$$

These, in fact, are the quantities which occur in the asymmetries.

For example, a state which starts as $|B^0\rangle$ at $t = 0$ oscillates at time t to the state

$$|B^0(t)\rangle = e^{-\frac{\Gamma}{2}t} e^{-i\bar{m}t} \left[\cos \frac{\Delta m}{2}t |B^0\rangle + ie^{-2i\beta} \sin \frac{\Delta m}{2}t |\bar{B}^0\rangle \right] \quad (27)$$

with Γ the common width of the two states, $\bar{m} = \frac{M_H + M_L}{2}$ and $\Delta m = M_H - M_L$. The decay of $|B^0\rangle$ and $|\bar{B}^0\rangle$ to a common final state f with amplitudes A and \bar{A} , respectively, produces the asymmetry

$$A(t) = \frac{\Gamma(t) - \bar{\Gamma}(t)}{\Gamma(t) + \bar{\Gamma}(t)} = -\text{Im} \left(e^{-2i\beta} \frac{\bar{A}}{A} \right) \sin \Delta mt. \quad (28)$$

The difference between $\Gamma(t)$ and $\bar{\Gamma}(t)$ comes about because sometimes B_d decays into f directly and sometimes it mixes to become a \bar{B}_d which then decays to f . The two decay paths are shown schematically in fig. (5). The observation of the asymmetry $A(t)$ is called CP-violation through mixing.⁴¹ There are many decay channels where these asymmetries occur and their measurement will determine the CKM angles and phase.⁴²

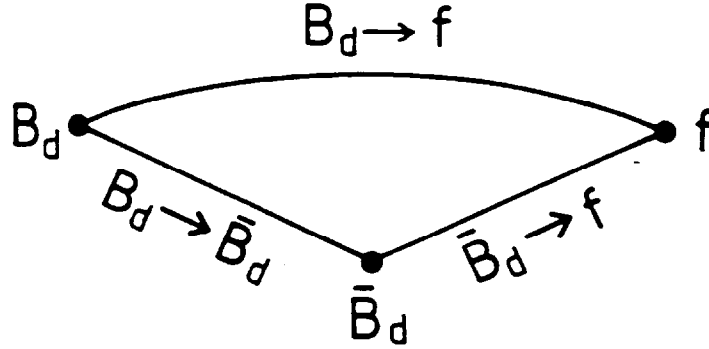


Fig. 5. CP violation through mixing.

For the CKM Paradigm the number of CP parameters is limited. The unitarity of the CKM matrix can be represented geometrically in terms of triangles, such as the one depicted in fig. (6). The three angles α , β , γ are the parameters to be measured

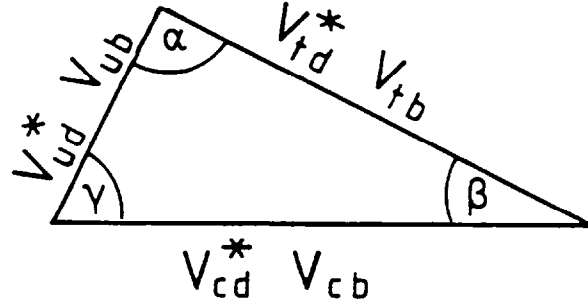


Fig. 6. The unitarity triangle.

directly by the CP asymmetries. We already know some limits for these angles³¹:

$$0.17 \leq \sin 2\beta \quad (29)$$

$$0.1 \leq \sin^2 \gamma \quad (30)$$

The angle β is the same angle appearing in Eqs. (23), (26) and (28). Many theoretical studies investigated decay channels which select specific angles. We review these results in the next subsection.

4.3 Probing the angles α , β and γ

In case that there is only one diagram for a specific decay the CKM elements factorize, i.e. they appear in A_f as an overall factor times a function which contains the hadronic structure and uncertainties (hadronic matrix element). The corresponding decay amplitude for the antiparticle is obtained by taking the complex conjugate

of the CKM factor. Therefore in a decay with a single diagram the hadronic matrix element drops out in Eq. (28). This property is extensively used to construct asymmetries free of hadronic uncertainties.

The classical example is the decay⁴³

$$B_d \rightarrow (J/\psi) + K_{CP}^0 \quad (31)$$

with K_{CP}^0 being either K_S or K_L . In both cases the final state is a CP eigenstate. This decay probes the angle β through the asymmetry

$$A(t) = -\sin \Delta m t \cdot \sin 2\beta. \quad (32)$$

The decay proceeds through the diagram in fig. (7) and is independent of the hadronic

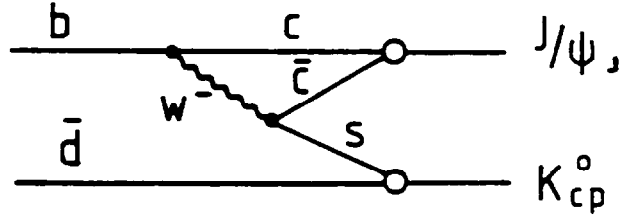


Fig. 7. The decay $B_d \rightarrow (J/\psi) + K_{CP}^0$.

matrix element. The decay has been observed with a branching ratio $3 \cdot 10^{-4}$. Many experiments concentrate their efforts on this gold-plated channel.

In case that the experiments can tag B^0 and \bar{B}^0 , then there is the opportunity to use their semi-inclusive decays

$$B^0 \rightarrow K_s X(c\bar{c}) \quad (33)$$

to establish CP-violation. It was proven⁴⁴ that it suffices for the final state to consist of a "self-conjugate" collection of particles and shown that the asymmetry for the reaction (33) is the same as in Eq. (32).

A similar analysis holds for the decays⁴⁵

$$B_s^0 \rightarrow K^+ D_s^- \quad \text{and} \quad B_s^0 \rightarrow \rho^- K_s^+ \quad (34)$$

where again only one diagram contributes (fig. 8). The formula for the asymmetry given in Eq. (32) holds for these decays when β is replaced by γ . Since the B_s^0 -decays are rare, there are also proposals to study B^\pm decays, like⁴⁶

$$B^\pm \rightarrow D_{CP}^0 + K^\pm \quad \text{and} \quad B^\pm \rightarrow \pi^0 K^\pm. \quad (35)$$

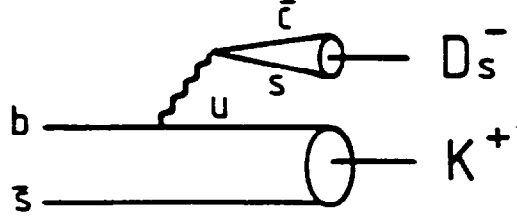


Fig. 8. The decay $B_s^- \rightarrow K^+ D_s^-$.

All decays are not as simple as the ones discussed so far. For instance, to probe the angle α we must study the decay $B_d^0 \rightarrow \pi^+ \pi^-$, where there is the tree diagram (9a) and in addition a penguin diagram (9b). The branching ratio for this decay

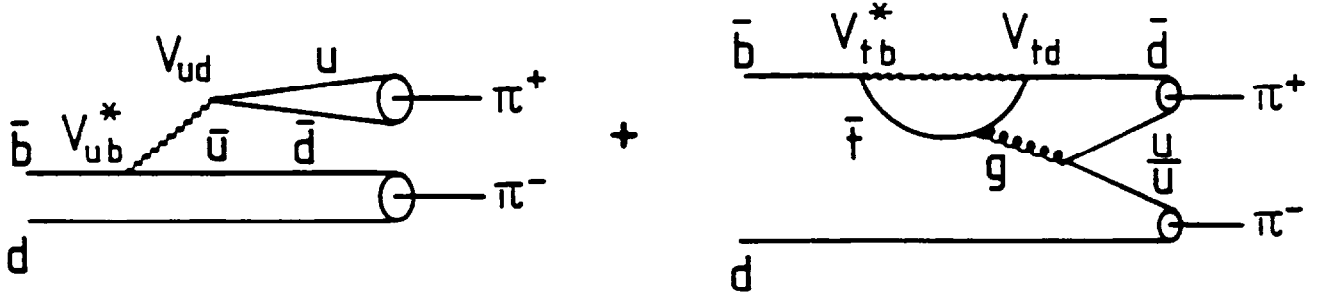


Fig. 9. The decay $B_d^0 \rightarrow \pi^+ \pi^-$.

mode is expected to be 10^{-5} and will require many events to determine α . In case that the penguin contribution is neglected, the asymmetry is

$$A = -[\sin \Delta m \cdot t] \cdot \sin 2\alpha. \quad (36)$$

Gronau and London⁴⁷ have shown that an isospin analysis of several decays can isolate the penguin contribution. This requires measuring $B^0 \rightarrow \pi^0 \pi^0$ which may be hard. Deshpande and He estimated the shift in the value of α produced by the penguin diagram and found^{48,49}

$$|\Delta \sin 2\alpha| < 0.14. \quad (37)$$

An isospin analysis will be able to determine α with greater precision.

At this time there are many other decay channels which are actively discussed. For shortage of space I only mention two of them. There are processes like $B_s \rightarrow \pi \varphi$, where the electroweak penguins dominate.⁵⁰ The second method studies the interference of the decay or production amplitudes with the width of a heavy resonance.⁵¹ The method is known as CP asymmetries induced by widths and was applied recently to inclusive decays.⁵¹

The ultimate goal of the B-meson decays will be to test the unitarity triangle through the relation $\alpha + \beta + \gamma = \pi$. This is an ambitious program which will take a long time. The immediate goal is to collect many events ($> 10^6$ events) and devise methods for tagging the B^0 and \bar{B}^0 mesons. There is evidence reported at this meeting for tagging B^0 and \bar{B}^0 in the LEP experiments. This is achieved by looking at the decays of B^{*-} and B^{*+} , as discussed in detail by J. Kroll in his talk. A similar tagging in the collider will be extremely valuable.

5. Baryon Generation

The CP phenomena discovered at the laboratory look also at the beginning of the universe. We know that in the universe, which started with zero baryon number, a baryon excess is generated. This happens in the presence of

- baryon violating decays, occurring
- at a time when C and CP are violated, bringing
- the universe out of thermal equilibrium.

In this picture which is very general there are three important issues for our problem:

- 1) Are there realistic scenarios with large CP effects to create the observed baryon asymmetry?
- 2) Are the CP asymmetries observed at the laboratory connected to the cosmological CP-violation at the early universe?
- 3) Are there remnants of the cosmological CP-violation besides ΔB , which can be observed and studied?

In this section I will discuss only the most popular scenarios for producing the baryon asymmetry.

5.1 Scenario A

In the first scenario the baryon asymmetry is generated at the phase transition. In the electroweak scale bubbles were formed randomly throughout the universe. Outside the bubbles $\langle H \rangle = 0$ and inside $\langle H \rangle \neq 0$. The bubbles are topological solutions and as the fermions and antifermions cross their boundaries, an excess of baryons is produced because the transition probabilities for fermions and antifermions are different.^{52,53} Actual calculations give different results. The baryon asymmetry generated is, sometimes, small because CP-violation is small in the standard model. The subject is still under active investigation. A new paper, submitted to this conference⁵⁴, introduces at a temperature much higher than TeV a new order parameter (Wilson line) which localizes fermions, ψ , but spreads out the CP conjugate states $\gamma_0 \gamma_2 \psi^*$. As the bubbles expand and fill the universe, an excess of fermions survives. As mentioned above, the subject of baryon generation at the phase transition is still under active development and a consensus is still to come.

5.2 Scenario B

The second scenario generates the baryon excess in grand unified theories. The original proposal was $SU(5)$ but many extensions are now available. In these theories we distinguish two types of symmetry breaking:

- i) CP-violation occurs in the decay amplitudes; these are ϵ' -type effects.
- ii) CP-violation may occur in the mass matrices which produces ϵ -type effects.

In the first case the baryon asymmetry is produced in the decay of heavy particles X and Y . CP is violated in the interference of the tree with a loop diagram (fig. 10). The baryon asymmetry generated is small because $(B - L)$ is conserved by the lower dimension operators. The $(B - L)$ quantum number is broken by higher order operators, but they are suppressed by factors (M_W/M_{GUT}) .

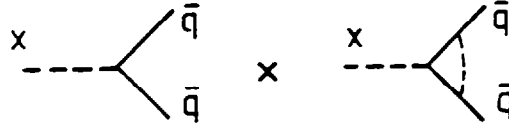


Fig. 10. Interference of tree with one-loop diagram.

Fukugita and Yanagida⁵⁵ observe that Majorana neutrinos change the lepton number by two units and they automatically produce a net $(B - L)$. They introduce CP-violation in the couplings of the Higgs particles to leptons and generate a lepton asymmetry in the decays of the heavy Majoranas. The lepton asymmetry is changed, later on, into a baryon asymmetry. The scheme is attractive but the effects are again small.

Finally ϵ -type effects were proposed recently. The lepton-antilepton oscillations in the above model⁵⁶ create physical states which are superpositions of Majorana neutrinos and their charge conjugate partners. These are produced by the finite parts of the self-energies, shown in fig. (11). Thus the physical states are not CP or

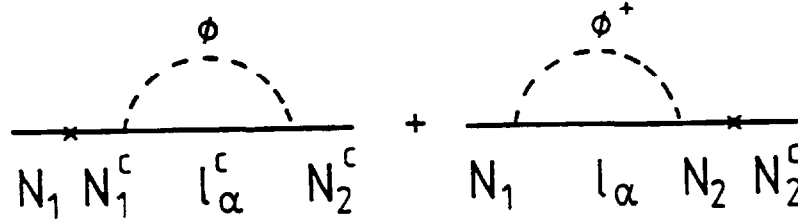


Fig. 11. One-loop diagrams contributing to $N_1 \rightarrow N_2$ transition.

lepton-number eigenstates. The heavy particles decay to ordinary leptons producing a lepton asymmetry. The lepton asymmetry is transferred to a baryon asymmetry in the electroweak phase transition. The effects produced in this scenario can be rather large.

6. Summary

I have described in this talk the great interest that exists on the breaking of discrete symmetries. I summarize my talk with two lists: what we know at present and what we expect in the foreseeable future.

6.1 Present

1. After many investigations CPT is still a good symmetry.
2. After serious studies we still do not know the origin of CP-violation. In fact we do not know if the symmetry originates explicitly in CKM-matrix, or if it has a deeper origin being broken spontaneously.
3. The discovery of the top quark is a great bonus. The top quark appears in box and penguin diagrams and its discovery eliminates many uncertainties in $E(x_t)$, $E(x_c, x_t)$, which in turn restrict the parameters η and ρ .
4. For $(\varepsilon'/\varepsilon)_K$ there are two experiments with two values: one large and one small. There are also two theoretical predictions: one large and one smaller. The ratio will be measured accurately in 1998.

6.2 Future

5. There are many tests with B-mesons and there are, justifiably, many experiments planned at CESR, LEP, HERA-B, colliders and B-meson factories (KEK and SLAC). They will eventually test $\alpha + \beta + \gamma = \pi$ (Unitarity Triangle). If the experimental results disagree with this relation we must go beyond the standard model.
6. In case of agreement, we must still explain many parameters of the standard model. There are already articles⁵⁷ which go beyond the standard model trying to relate the parameters within a larger symmetry.
7. We still need independent tests of time reversal, like electric dipole moments D_n , D_e , ..., D_τ .
8. Mixing and CP-violating effects for the D mesons are predicted to be small, but there could be surprises. In case there are abnormally large CP-violating effects, their time development can also determine the mass difference, Δm , of the neutral D mesons.⁵⁸ D meson studies are possible in the τ -charm factory.
9. Up to now, there is no evidence for CP or T violation in the lepton sector. The signals are asymmetries which involve triple products of vectors like $\langle \hat{P}_{in} \cdot (\hat{P}_e \times \hat{P}_\mu) \rangle$. There are few theoretical predictions on the magnitude of these effects and the τ -charm factory has a unique opportunity to search for them.

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